

DISKY ELLIPTICAL GALAXIES AND THE ALLEGEDLY OVER-MASSIVE BLACK HOLE IN THE
COMPACT MASSIVE ‘ES’ GALAXY NGC 1271

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Abstract

While spiral and lenticular galaxies have *large-scale* disks extending beyond their bulges, and most local early-type galaxies with $10^{10} < M_*/M_\odot < 2 \times 10^{11}$ contain a disk (e.g., ATLAS^{3D}), the early-type galaxies do possess a range of disk sizes. The edge-on, *intermediate-scale* disk in the ‘disky elliptical’ galaxy NGC 1271 has led to some uncertainty as to what is its spheroidal component. Walsh et al. reported a directly measured black hole mass of $(3.0^{+1.0}_{-1.1}) \times 10^9 M_\odot$ for this galaxy; which they remarked was an order of magnitude greater than what they expected based on their derivation of the host spheroid’s luminosity. Our near-infrared image analysis supports a small embedded disk within a massive spheroidal component with $M_{sph,*} = (0.9 \pm 0.2) \times 10^{11} M_\odot$ (using $M_*/L_H = 1.4^{+0.13}_{-0.11}$ from Walsh et al.). This places NGC 1271 just 1.6-sigma above the near-linear $M_{bh}-M_{sph,*}$ relation for early-type galaxies. Therefore, past speculation that there may be a systematic difference in the black hole scaling relations between compact massive early-type galaxies with intermediate-scale disks, i.e. ES galaxies such as NGC 1271, and early-type galaxies with either no substantial disk (E) or a large-scale disk (S0) is not strongly supported by NGC 1271. We additionally (i) show how ES galaxies fit naturally in the (‘bulge’-to-total)-(morphological type) diagram, while noting a complication with recent revisions to the Hubble-Jeans tuning-fork diagram, (ii) caution about claims of over-massive black holes in other ES galaxies if incorrectly modelled as S0 galaxies, and (iii) reveal that the compact massive spheroid in NGC 1271 has properties similar to bright bulges in other galaxies which have grown larger-scale disks.

Subject headings: galaxies: elliptical and lenticular, cD — black hole physics — galaxies: individual (NGC 1271) — galaxies: nuclei — galaxies: photometry — galaxies: structure

1. INTRODUCTION

Over the past decade, there has been an increasing interest in the fate of the compact, massive galaxies seen at $z \sim 2 \pm 0.5$ (e.g. Daddi et al. 2005; Toft et al. 2007; Trujillo et al. 2007; Damjanov et al. 2009, 2014; Weinzirl et al. 2011; Prieto et al. 2013; van Dokkum et al. 2008, 2015; Carollo et al. 2013; Zahid et al. 2016; Andreon et al. 2016). In mid-2011 Graham pointed out that these galaxies have the same physical properties as the spheroidal component of some local lenticular galaxies (Graham 2013). Dullo & Graham (2013) further advocated that disks may have formed in and around these high- z mass concentrations to build the local lenticular galaxies. Nearly two dozen $z \approx 0$ galaxies with massive compact spheroidal components have since been presented in Graham, Dullo & Savorgnan (2015, hereafter GDS15; see also Valentinuzzi et al. 2010a,b; Poggianti et al. 2013a,b; Saulder et al. 2015; Carollo et al. 2016; de la Rosa et al. 2016). This sample included early-type galaxies in which the disk had not grown into a large-scale disk that dominates the light at large radii but was instead an intermediate-scale disk¹ embedded within the spheroidal component of the galaxy². Liller (1966) dis-

covered such galaxies, bridging the E and S0 morphological types (Hubble 1936), and she designated them *ES* galaxies. They have subsequently been referred to as “disk ellipticals” (Nieto et al. 1988) and “disky ellipticals” (Simien & Michard 1990; Michard & Marchal 1993; Andreon et al. 1996). Obviously, when a disk grows sufficiently large, the *total* galaxy is no longer compact even though the spheroidal component still is. Such disk growth would therefore result in an apparent decrease in the number density of compact *galaxies* with decreasing redshift but no reduction to the actual number of the compact *spheroids* themselves.

NGC 1277 was one such ES galaxy noted in GDS15 — after van den Bosch et al. 2012 identified the galaxy as compact and massive³ — as was NGC 1332 (Savorgnan & Graham 2016b), NGC 5493 (Krajinović et al. 2013) and NGC 5845 (Jiang et al. 2012). NGC 1271 is another nearby, compact early-type galaxy (Brunzendorf & Meusinger 1999) that contains a nearly edge-on, intermediate-scale disk. It was first recognized as having an unusually small half-light radius for its luminosity in the catalog of Strom & Strom (1978), with such galaxies labelled as ‘compact galaxies’ as far back as Zwicky & Kowal (1968) and Zwicky & Zwicky (1971).

Galaxies with intermediate-scale disks can be more akin to the spheroidal component of lenticular galaxies that acquired large-scale disks than they are to com-

tains an embedded, nearly edge-on, disk (Graham et al. 2012).

³ Graham et al. (2016) have identified its spheroid component as compact and massive.

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¹ Although we use the term *intermediate-scale* disk to distinguish it from both *large-scale* disks which dominate the light at large radii, and *nuclear* disks which are typically tens to a few hundred parsec in size (e.g. Balcells et al. 2007), we point out that a continuum of disk sizes exists.

² Intermediate-scale disks are not just confined to compact massive galaxies; the dwarf early-type galaxy LEDA 074886 also con-

plete lenticular galaxies. As noted above, although such intermediate-scale disks are not unusual, they may be somewhat unfamiliar to readers more versed with the bulge/disk structure of spiral and lenticular galaxies. The spheroidal stellar component of spiral galaxies presents itself as a central bulge encased within a disk: that is, the spheroid does not dominate the light at large radii — as noted by the warning in Figure 7 from Graham (2001). However, early-type galaxies *can* have spheroidal components which dominate the galaxy light at both inner and outer radii. This situation can arise when a disk has not grown large enough to dominate the light at large radii. Galaxies in clusters may well be particularly prone to this situation due to ram pressure stripping (Gunn & Gott 1972) removing their disk-building gas supply, and “Strangulation” (Larson et al. 1980; Bekki et al. 2002) — which also operates in galaxy groups (Kawata & Mulchaey 2008) — cutting off their gas supply. This may contribute to the compact massive galaxies found in clusters by the Wide-field Nearby Galaxy-cluster Survey (WINGS) collaboration (e.g. Valentinuzzi et al. 2010a; see also Nantais et al. 2013).

Careful bulge/disk decompositions are required if one is to avoid comparing ‘apples and oranges’ and subsequently misinterpreting systematic offsets in various parameter scaling diagrams. For example, it is not appropriate to consider such small disks as the ‘bulge’ component of a galaxy, nor to consider only the inner portion of the spheroidal component (where its light produces a central bulge in the radial light profile above the intermediate-scale disk) as the complete spheroidal component of a galaxy, nor to confuse the inner portion of the spheroid as an encased bulge surrounded by a disk plus a separate envelope that is actually the outer portion of the spheroid.

Considering the ‘bulge’ component of a galaxy to be the smallest-sized component in their multiple Sérsic model descriptions of NGC 1271, Walsh et al. (2015; hereafter W2015) derived a bulge mass for NGC 1271 of $5.4 \times 10^{10} M_{\odot}$. This was the midpoint of their two estimates ($8.7 \times 10^{10} M_{\odot}$ and $2.3 \times 10^{10} M_{\odot}$) obtained by fitting 2 and then 3 Sérsic components to the galaxy image. Their uncertainty as to the actual spheroidal component of this galaxy led them to adopt the average mass from the smallest-sized component of both decompositions, which they then used in the near-linear $M_{\text{bh}}-M_{\text{sph},*}$ relation from Kormendy & Ho (2013) to predict a central black hole mass that was an order of magnitude lower than their directly measured black hole mass of $3.0^{+1.0}_{-1.1} \times 10^9 M_{\odot}$. That is, they reported the detection of an “over-massive” black hole in NGC 1271 relative to its bulge (their Figure 10). From this, they concluded that there could be systematic differences in the black hole scaling relations between compact massive galaxies (i.e. spheroids with intermediate-scale disks such as NGC 1271 and NGC 1277) and the other spheroids which have been used to construct the (black hole)–(host spheroid) mass scaling relation, i.e. the spheroidal component of: galaxies with larger-scale disks; normal elliptical galaxies; and brightest cluster galaxies. W2015 went on to remark that a difference in the black hole scaling relations implies a different growth path, i.e. evolution, for black holes in such galaxies (see also Ferré-Mateu et

al. 2015).

Given that the above interpretation effectively rests on the mass of the black hole predicted from the stellar mass of the host spheroid, in Section 2 we perform a spheroid/disk decomposition of NGC 1271 to independently determine the mass of its spheroidal component, and then predict the mass of its central black hole using the latest $M_{\text{bh}}-M_{\text{sph},*}$ relation⁴. In addition to the surface brightness profile, we use both the ellipticity profile and the “disky / boxy” B_4 profile — which quantifies the deviations of the isophotes from ellipses (Carter 1978, 1979, 1987; Jedrzejewski 1987; Bender & Möllenhoff 1987; Ebneter et al. 1988; Bender 1988; Bijaoui et al. 1989) — to reveal the radial extent of the disk in NGC 1271. We do so using the routine described in Ciambur (2015), which improves upon the prescription used in the popular IRAF task ELLIPSE (Jedrzejewski 1987). We show that the disk resides wholly within the spheroidal component of NGC 1271 which dominates the light at large radii. Our analysis results in a larger spheroid mass and thus a lower (black hole)-to-spheroid mass ratio than was recently highlighted by W2015. In Section 3 we discuss this result, placing NGC 1271 in the $M_{\text{bh}}-M_{\text{sph},*}$ diagram, and we additionally reveal that the compact spheroidal component of NGC 1271 is also not an outlier in either the mass-size or the mass-density diagram. We go on to discuss the evolution, or lack thereof, of compact massive spheroids, and also reveal how ES galaxies relate to other galaxies in a familiar classification diagram involving the spheroid-to-disk flux ratio and galaxy morphological type. Our main conclusions are briefly presented in Section 4.

Following W2015, we adopt their Perseus galaxy cluster (Abell 426) distance of 80 Mpc to NGC 1271. Together with their use of $H_0 = 70.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$ and $\Omega_{\Lambda} = 0.73$, this gives a Hubble expansion redshift $z = 0.0188$ and a scale of 379 parsec per arcsecond (Wright 2006).

2. IMAGING DATA AND ANALYSIS

We have used an archived *Hubble Space Telescope* (*HST*) image taken with the *Wide Field Camera 3* (*WFC3*) and the near-infrared *F160W* filter. This image is a distortion corrected *PyDrizzle* output, obtained from the combination of 2 individual exposures, with a total integration time of 898.5 seconds and a pixel size of $0.128 \text{ arcsec pixel}^{-1}$. We manually checked that the background subtraction had been correctly performed, and built a mask for the contaminating sources. Figure 1 shows a cutout of NGC 1271 from the larger image, and our mask. NGC 1271 can be seen to contain a nearly edge-on, stellar disk. While nearly edge-on, *large-scale* disks result in early-type galaxy isophotes becoming increasingly elongated at large radii, embedded *intermediate-scale* disks do not. Instead, the outer

⁴ Graham (2016) provides a detailed review of the development of the $M_{\text{bh}}-M_{\text{sph}}$ relation, from Dressler (1989) and Yee (1992) up until the bent relation in Graham & Scott (2015; see also the models by Lu & Mo 2015 and Fontanot, Monaco & Shankar 2015). In addition to describing the $M_{\text{bh}}-M_{\text{sph},*}$ relation, Graham (2016) contains an extensive bibliography to explain how and why we came to believe in (super-massive) black holes.

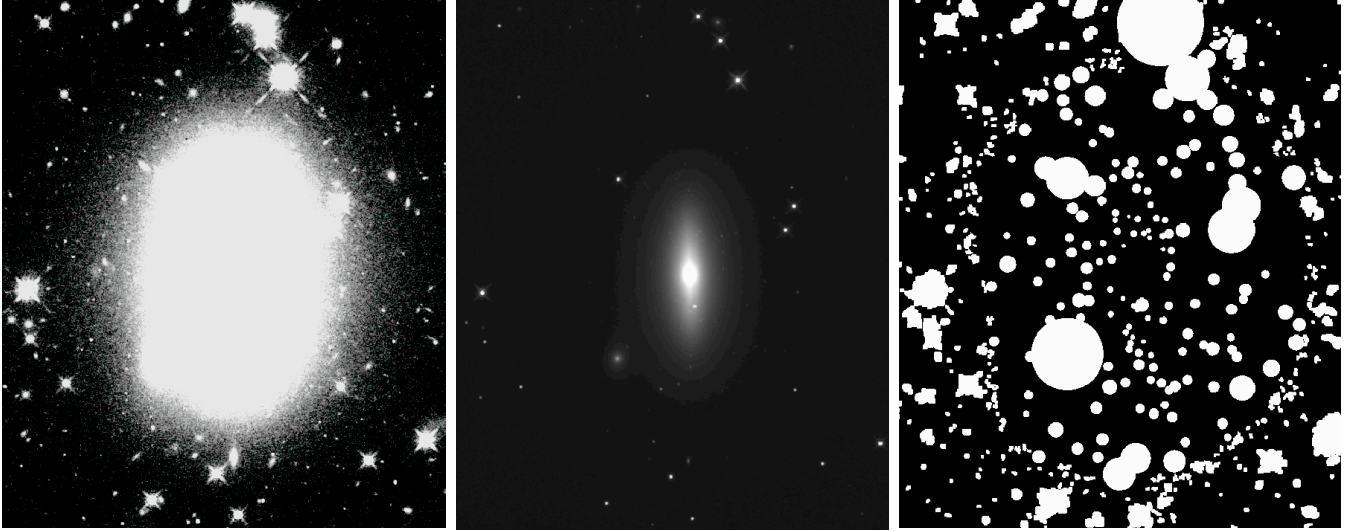


FIG. 1.— Masking the image. Left panel: *HST/WFC3 IR/F160W* image of NGC 1271. Middle panel: Different stretch to show the embedded, intermediate-scale disk. Right panel: Image mask used for subsequent galaxy modeling. This image is $\sim 88''$ high by $\sim 73''$ wide. North is roughly toward the upper left corner while east is roughly toward the lower left corner.

isophotes become rounder (reflecting the ellipticity of the galaxy’s spheroidal component) as the influence of the disk diminishes at larger radii.

2.1. 1D light profile analysis

We performed an isophotal analysis of NGC 1271 using the task ISOFIT (Ciambur 2015), which fit quasi-elliptical isophotes to the galaxy image. ISOFIT is a modified version of the IRAF task ELLIPSE (Jedrzejewski 1987), and is much more capable of modeling features such as diskyness, which is particularly relevant in the case of NGC 1271. The ISOFIT task generates a major-axis light profile along with all the associated terms that describe the shape of each isophote and enable one to construct an accurate 2D galaxy model, with the position angle profile, the ellipticity profile, and the Fourier harmonic terms describing the deviations from pure elliptical isophotes at each radius. Our reconstructed image of NGC 1271 can be seen in the middle panel of Figure 2. As the right-hand panel of Figure 2 reveals, this reconstruction provides a clean representation of the galaxy, which is then suitable for analysis through the fitting of galaxy components.

The major-axis surface brightness profile was additionally mapped to the so-called ‘equivalent-axis’, i.e. the geometric mean of the major (a) and minor (b) axis ($R_{\text{eq}} = \sqrt{ab}$), which is equivalent to the radius of the ‘circularized’ isophotes. This axis is such that if the area interior to each isophote was enclosed by a circle, then the radius of that circle is associated with the surface brightness of the isophote. With the equivalent-axis light profile one can then use spherical geometry for the purposes of calculating the integrated surface brightness, i.e. the magnitude. Both the major-axis and the equivalent-axis surface brightness profiles (in the Vega system) are shown in Figure 3.

The one-dimensional point spread function (PSF) was characterized using the IRAF task IMEXAMINE. By fitting a Gaussian function to the radial intensity profiles of 12 bright stars in the image, we measured the ‘full width at half maximum’ (FWHM) and obtained an average value of 0.24 arcsec. We then performed a galaxy decom-

position with the PROFILER software (Ciambur 2016). In essence, at each iteration in the fitting process, a two-component (spheroid + disk) model was constructed and convolved with a Gaussian function to replicate the “seeing” (PSF) effects in the data⁵, and then matched to the data over the inner $30''$. While a core-Sérsic profile (Graham et al. 2003) is expected for the spheroidal component of NGC 1271 (see Graham & Scott 2013) given its high central velocity dispersion, it does not appear to have a depleted core. NGC 1277 is another galaxy with a high central velocity dispersion and no partially-depleted core (van den Bosch et al. 2012; Graham et al. 2016). Indeed, rather than a deficit of stars at its core, NGC 1277 contains an additional nuclear component.

Dullo & Graham (2014, their section 3.4) provide a discussion of why, when modeling the distribution of light in galaxies, one should not simply arbitrarily add components until they are satisfied with the amplitude of the (data–model) residuals. Several examples of where this has led to questionable results are provided there⁶. The Sérsic (1963) $R^{1/n}$ function that we used here has previously been described in Caon et al. (1993) and Graham & Driver (2005), and we used a standard exponential disk model for the equivalent-axis light profile, such that the intensity $I_{\text{disk}}(R_{\text{eq}}) = I_{0,\text{disk}} \exp(R_{\text{eq}}/h_{\text{exp}})$. The major-axis light profile, for which the disk dominates from ~ 3 to ~ 20 arcseconds, required the edge-on disk model (van der Kruit & Searle 1981), which is such that the intensity

$$I_{\text{disk}}(R_{\text{maj}}) = I_{0,\text{disk}} \left(\frac{R_{\text{maj}}}{h_{\text{edge-on}}} \right) K_1 \left(\frac{R_{\text{maj}}}{h_{\text{edge-on}}} \right), \quad (1)$$

⁵ Perhaps not surprisingly given the radial extent the light-profile, We found similar results using a Moffat function to represent the PSF and its Airy-ring wings.

⁶ Readers interested in the structure of light profiles, and the historical development of how they are modeled, may wish to refer to Graham (2013).

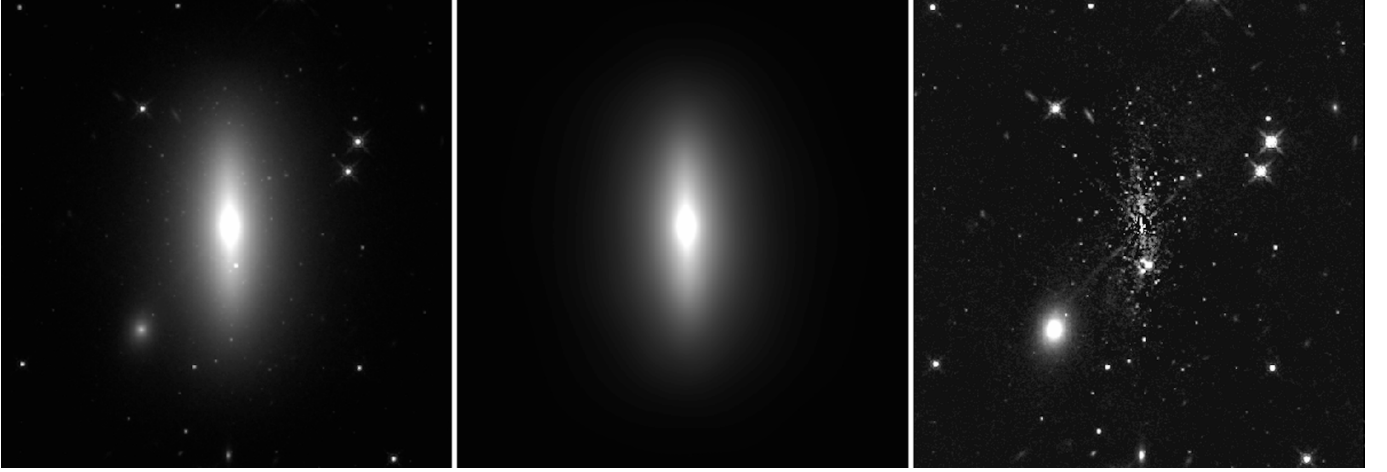


FIG. 2.— Data, model, residual. Left panel: Data revealing the near edge-on disk in NGC 1271, with a $2\times$ zoom of Figure 1. Middle panel: Galaxy reconstructed with the new CMODEL (construct model) task in IRAF, rather than the BMODEL (build model) task, used in combination with the new ISOFIT task rather than the ELLIPSE task (see Ciambur 2015 for details). A similar image display stretch as in the left panel has been used. Right panel: Residual after subtracting the middle panel from the left panel, and adjusting the display stretch to linear so as to effectively amplify the residuals. A multitude of star clusters can be seen. This image is $\sim 32''$ high by $\sim 31''$ wide.

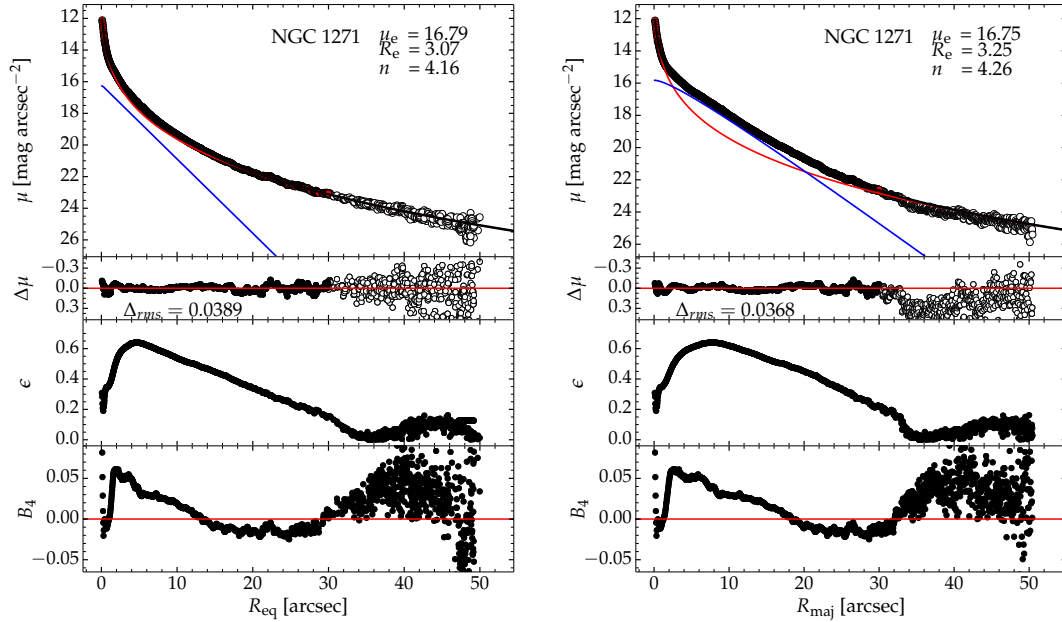


FIG. 3.— Left panel: The geometrical mean (\sqrt{ab}) ‘equivalent axis’ light profile (calibrated to the Vega magnitude system), extracted from the middle panel of Figure 2, is modeled with a Sérsic function (red) for the galaxy’s spheroidal component plus an exponential function (blue) for the galaxy’s disk. Points denoted with open circles were deemed less reliable and not used in the fit. The Sérsic parameters are inset in the panel, and the residual profile is shown in the panel immediately below. Beneath this is the ellipticity and B_4 profiles derived using the new IRAF task ISOFIT (Ciambur 2015). Right panel: Major-axis (a) light profile, fit using the inclined disk model (blue) and a Sérsic function (red) for the spheroidal component.

where $h_{\text{edge-on}}$ is a radial scale and K_1 is a modified first-order Bessel function. Unlike with the exponential model, $h_{\text{edge-on}}$ is not the radius where the disk intensity has dropped by a factor of e (≈ 2.718).

The results of fitting the above models are shown in Figure 3, which additionally reveals the humped ellipticity profile (and the fourth harmonic profile: positive B_4 equals disk, negative B_4 equals boxy) that is characteristic of the embedded disks of ES galaxies (Liller 1966). The goodness of the fit is measured by the quantity $\Delta = \sqrt{\sum_{i=1,N}(\text{data}_i - \text{model}_i)^2 / (N - \nu)}$, where N is the number of data points and ν ($= 5$) is the number of

model parameters involved (2 disk and 3 spheroid). The magnitudes, luminosities and ultimately stellar masses (see Section 2.3) of the spheroid and the embedded disk were derived from the equivalent-axis light profile, as discussed above and detailed in the Appendix of Ciambur (2015). These values are provided in Table 1.

Given that disks have a typical thickness, i.e. ratio of vertical scale-height to radial scale-length of 0.20–0.25 (e.g. Sandage, Freeman & Stokes 1970; Bizyaev et al. 2014, their Figure 4), we can expect the equivalent axis

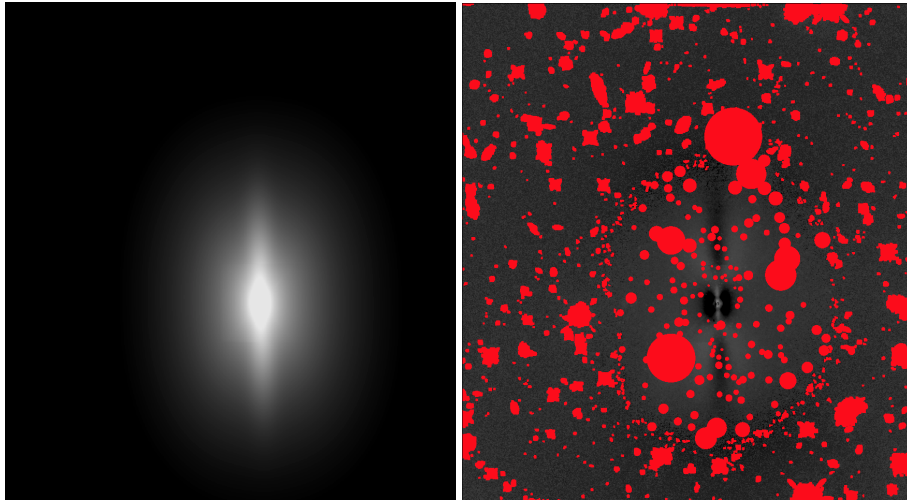


FIG. 4.— Left panel: 2D GALFIT model (Sérsic bulge + exponential disk) (log scaling). Right panel: Residual image divided by the ‘sigma’ image (greyscale, linear scaling), and the mask used (red, linear scaling). This image is roughly $110''$ high by $116''$ wide.

of a near edge-on disk to have an exponential scale-length equal to $\sqrt{0.2}$ to $\sqrt{0.25}$ (0.45 to 0.5) times that of the major-axis’ exponential scale-length. The exponential disk model shown in the left hand panel of Figure 3 has a scale-length of $2''.31$, while the edge-on disk model shown in the right hand panel of Figure 3 has dropped in intensity by a factor of e from its central value by the radius $R_{\text{maj}} = 5''.19$, giving a minor-to-major axis ratio of $(2.31/5.19)^2 = 0.20$.

We note that the disk is likely to be more complicated than assumed in our models. For instance, at around $R_{\text{maj}} = 32''$, the radial intensity profile of the disk may truncate or break to a more rapid rate of decline (see the right hand panel of Figure 3). In addition, the double hump in the B_4 profile at $R_{\text{maj}} \approx 3''$ and $6''$ is suggestive of another component. There may be a bar or an inner ring in addition to the intermediate-scale disk. Furthermore, the disk component of the equivalent-axis light profile is probably only approximately described by the exponential model given the edge-on nature of the disk. We trialed many variations, such as fitting equation 1, and fitting the expression appropriate for the minor-axis light profile of the edge-on disk model (van der Kruit & Searle 1981), and locking the central surface brightness to exactly match the value derived from the fit to the major-axis light profile, plus locking the scale-length to 0.45 times the asymptotic value seen at large radii in the fit to the major-axis light profile (right hand panel of Figure 3) where, admittedly, the disk’s ‘light profile’ shape is not well constrained. Not surprisingly, none of these variations had a large impact on the derived spheroid magnitude; the greatest departure was just 0.15 mag. We therefore conclude that refinements to the disk model will not have a large impact on the spheroid magnitude.

We additionally tested the robustness of our decomposition results to the PSF characterization by using a range of FWHM between $0''.19 - 0''.26$ (the values reported in the literature, e.g. Cassata et al. 2010; Windhorst et al. 2011). We found this changed the model parameters very little: the variation in estimated bulge magnitude was within 0.01 mag, while the Sérsic index along the major-axis varied by just 0.02.

2.2. 2D image analysis

We additionally performed a 2D image decomposition using the software GALFIT3 (Peng et al. 2010). We obtained an image of the PSF from the TINYTIM software (Krist, Hook & Stoeckl 2011; Biretta 2014). However because this PSF is narrower than the ‘real’ stars in our image, we built a broader PSF image by convolving a 2D Gaussian profile with the PSF image from TINYTIM. The advantage of this method (C. Peng, private communication) is to obtain a 2D PSF that is wider than the TINYTIM PSF, but maintains the asymmetric features of the TINYTIM PSF (e.g. wings and spikes). We modeled the galaxy with a Sérsic component for the spheroid and an exponential function for the disk. The minor-to-major axis ratio for the fitted disk model was equal to 0.22. As noted above, this is basically equal to the typical thickness of galaxy discs, i.e. the (vertical scale-height)-to-(radial scale-length) ratio observed in edge-on discs. We note that using a Sérsic model for the edge-on disk, rather than an exponential model, had no significant impact on the results (Figure 4 and Table 1).

Our 2D analysis is similar to the 2-component fit reported in Table 4 of W2015, in that the disk component has similar parameters. While we also both report a Sérsic index ~ 6 for the more massive component, W2015 obtain notably more elongation from their fit, such that they report an axis ratio of 0.54 for their Sérsic model, compared to our value of 0.69, and they report a major-axis half-light radius of $R_e = 5''.23$ for the spheroid compared to our value of $3''.08$. An axis ratio of 0.54 is too low to match the outermost ellipse drawn in Figure 1 of W2015, which approximates the isophote at $R_{\text{major-axis}} = 25''$ and has an axis ratio of 0.65.

The rigidity of the 2D model’s components (i.e. the constant position angle and ellipticity of the spheroid and disk), and the treatment of the diskyness, meant that our 2D model was not able to fully reproduce the galaxy light in the way that the 1D analysis did. This is evident in the residual image seen in the right hand panel of Figure 4, which can be contrasted with the right hand panel of Figure 2. Despite the better result using the 1D approach, the difference in the magnitude for both the spheroid and the disk is not more than 0.3 mag when

using the 2D approach. More specifically, the 2D model results in a spheroid that is just 22% fainter (see Table 1). Given that the 1D light profile is constructed by fully capturing the galaxy light (see Figure 2), while also accounting for deviations from elliptical isophotes in terms of Fourier harmonics, this is our preferred analysis for the estimate of the spheroid brightness. Fitting the 1D light profile, within the inner $30''$, the difference between our 2-component spheroid+disk model and the data is less than $0.15 \text{ mag arcsec}^{-2}$, while the average difference is less than $0.04 \text{ mag arcsec}^{-2}$ (Figure 3).

2.3. Galaxy parameters

Table 1 lists the structural parameters that we have obtained for NGC 1271. We correct the observed, apparent magnitudes of each component for $2.5\log(1+z)^2$ (≈ 0.04) mag of cosmological redshift dimming, and 0.08 mag of Galactic extinction (Schlafly & Finkbeiner 2011, via the NASA/IPAC Extragalactic Database: NED⁷). The intermediate-scale disk of NGC 1271 does not appear to contain any obvious dust features beyond the inner $1''$, and as such we have elected to not apply an internal dust correction which would act to brighten the disk and spheroid (Driver et al. 2008).

Using a distance modulus⁸ of 34.52 , and a solar H -band absolute magnitude of $+3.33$ mag (Vega: Bessell et al. 1998), the corrected absolute magnitude of the spheroid (-23.71 mag) corresponds to an H -band luminosity of $6.43 \times 10^{10} L_{\odot}$. W2015 report an H -band stellar mass-to-light ratio of $1.40^{+0.13}_{-0.11}$ for NGC 1271, and thus we have a stellar mass of $9.00 \times 10^{10} M_{\odot}$ for the spheroidal component of NGC 1271. Coupling the 0.15 magnitude uncertainty on the spheroid magnitude derived from the 1D light profile analysis with the above uncertainty on the mass-to-light ratio, we roughly have that $M_{\text{sph},*} = (9 \pm 2) \times 10^{10} M_{\odot}$.

Our spheroid-to-disk mass ratio is 3.7 (see Table 1). For reference, the 2-component fit by W2015 reported a spheroid-to-disk mass ratio equal to 4.1 and a bulge mass of $8.7 \times 10^{10} M_{\odot}$, in excellent agreement with our results. While that mass was their upper limit, the value of $9 \times 10^{10} M_{\odot}$ is our nominal value. W2015 also fit a 3-component model to NGC 1271, with the third component having a major-axis half-light radius of $0''.61$ and a stellar mass of $2.2 \times 10^{10} M_{\odot}$. They thought that this might be the actual “bulge” (i.e. the spheroid) to be used in the $M_{\text{bh}}-M_{\text{sph}}$ scaling relation. As they were unsure as to the spheroidal component of this massive early-type galaxy, they averaged these two masses and proceeded by assuming a mean spheroid mass of $5.4 \times 10^{10} M_{\odot}$.

The location of NGC 1271’s spheroid, as determined by our analysis, is shown in the mass-size and mass-density diagrams in Figure 5. It appears to be a common object, over-lapping with the physical properties of other massive bulges. An expression for the curved relation describing the distribution of the early-type galaxies in Figure 5a can be found in Graham (2013, his section 3.2.2; see also Lange et al. 2015, their Figure 6).

2.4. Predicted Black hole mass

We predict the black hole mass in NGC 1271 using three relations related to the spheroidal component of galaxies (Table 2).

Using the stellar mass of the spheroidal component of NGC 1271, the ‘Sérsic’ $M_{\text{bh}}-M_{\text{sph},*}$ relation in Scott et al. (2013), is such that

$$\begin{aligned} \log(M_{\text{bh}}/M_{\odot}) &= (7.89 \pm 0.18) \\ &+ (2.22 \pm 0.58) \log [M_{\text{sph},*}/2 \times 10^{10} M_{\odot}]. \end{aligned} \quad (2)$$

Given $M_{\text{sph},*} = 9.00 \times 10^{10} M_{\odot}$, and assigning a

⁷ <http://nedwww.ipac.caltech.edu>

⁸ Based on a distance of 80 Mpc .

TABLE 1
GALAXY MODEL’S COMPONENT PARAMETERS.

Component	R_e (arcsec / kpc)	h_e (arcsec / kpc)	n	(b/a)	m_H (mag)	M_H (mag)	L_H $10^{10} L_\odot$	M_*/L_H M_\odot/L_\odot	M_* $10^{10} M_\odot$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
<i>2D modeling of the image (major-axis scale sizes)</i>									
Spheroid	3.08 / 1.17	...	5.84	0.69	11.22	−23.42	5.01	1.4	7.01
Disk	...	3.99 / 1.51	1.00	0.22	12.08	−22.56	2.27	1.4	3.18
<i>1D modeling of the major-axis light profile</i>									
Spheroid	3.25 / 1.23	...	4.26	...	...	...	...	...	...
Disk	...	5.19 / 1.97	1.00	...	...	...	...	...	...
<i>1D modeling of the equivalent-axis light profile</i>									
Spheroid	3.07 / 1.16	...	4.16	1.00	10.95	−23.69	6.43	1.4	9.00
Disk	...	2.31 / 0.88	1.00	1.00	12.38	−22.26	1.72	1.4	2.41

Column 1: Model component that was fit to the light distribution. Column 2: Effective half light radius. Column 3: Radius where the disk’s intensity is e (≈ 2.718) times fainter than its central intensity (Note: the edge-on disk model used to describe the major-axis light profile has a radial scale $h_{\text{edge-on}}$ equal to $3''.13$.) Column 4: Sérsic index. Column 5: Component axis-ratio. Column 6: Observed (uncorrected) H -band apparent magnitude (Vega). Column 7: (Corrected, by 0.12 mag, see the text for details) H -band absolute magnitude. Column 8: H -band solar luminosity. Column 9: H -band Stellar mass-to-light ratio. Column 10: Stellar mass.

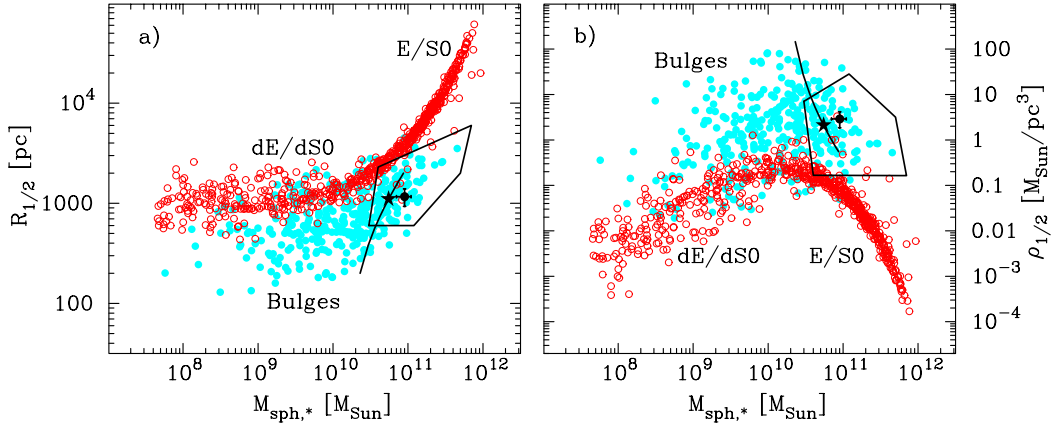


FIG. 5.— Panel a) Projected half-light radius ($R_{1/2} \equiv R_e$) versus stellar mass for nearby early-type galaxies and the bulges of nearby spiral, lenticular and elliptical galaxies. Panel b) Internal stellar-mass density within the radius ($4/3 \times R_{1/2}$) containing half the stellar mass plotted against the total stellar mass. Our estimate for NGC 1271 is shown by the black dot, while the range in mass and radii according to W2015 is shown by the black curve, with their midpoint marked by the black star. The distribution of compact massive galaxies at $z \sim 1.5$ — as given by Damjanov et al. (2009, their Figure 5) — is denoted by the 5-sided boundary which can be seen to overlap with the massive bulges at $z \approx 0$ shown here. Adapted from Figure 1 in Graham (2013).

20% uncertainty to this value⁹, one has the prediction $\log(M_{\text{bh}}) = 9.34 \pm 1.01$ ($M_{\text{bh}} = 2.19 \times 10^9 M_\odot$ with an order or magnitude uncertainty). This agrees well with the reported measurement from W2015 of $(3.0^{+1.0}_{-1.1}) \times 10^9 M_\odot$. The large uncertainty in the estimated value is dominated by the 0.90 dex of intrinsic scatter in the $\log(M_{\text{bh}})$ direction about that Sérsic $M_{\text{bh}}-M_{\text{sph},*}$ relation (Scott et al. 2013).

For a black hole of this mass, residing in a spheroid with a velocity dispersion $\sigma = 276 \text{ km s}^{-1}$ (W2015), its sphere of influence $r_h \equiv GM_{\text{bh}}/\sigma^2 = 0''.32$. For reference, the Near-infrared Integral Field Spectrometer (NIFS; McGregor et al. 2003) data used by W2015 to determine the black hole mass had a point-spread function which was represented by the sum of two Gaussians with dispersions of $0''.16$ and $0''.43$ and a 0.61:0.39 Strehl ratio weighting.

Since submitting this work, a new relationship for

⁹ See section 3.3 in Graham & Scott (2013) to understand how this uncertainty propagates through to the predicted black hole mass. Following that study, an intrinsic scatter of 0.90 dex in the $\log(M_{\text{bh}})$ direction has been used here for equation 2.

early-type galaxies has become available (Savorgnan et al. 2016), and is such that

$$\log(M_{\text{bh}}/M_\odot) = (8.56 \pm 0.07) + (1.04 \pm 0.10) \log [M_{\text{sph},*}/10^{10.81} M_\odot], \quad (3)$$

with an intrinsic scatter ($\sigma_{\text{intrinsic}}$) of about 0.48 dex in the $\log(M_{\text{bh}})$ direction. This relationship was established using the careful galaxy decompositions presented in Savorgnan & Graham (2016a), which revealed problems with many past works. Using $M_{\text{sph},*} = 9 \times 10^{10} M_\odot$, this relation gives $\log(M_{\text{bh}}) = 8.71 \pm 0.49$, or $M_{\text{bh}} = (0.51^{+1.07}_{-0.35}) \times 10^9 M_\odot$ (1-sigma uncertainties). While this is 5.9 times lower than the reported black hole mass of $3 \times 10^9 M_\odot$, the upper 2-sigma bound on this estimated mass is $4.9 \times 10^9 M_\odot$, encompassing the reported black hole mass. The reported black hole mass is offset by 0.77 dex from equation 3, or 1.6 times $\sigma_{\text{intrinsic}}$. Refining the scatter about the $M_{\text{bh}}-M_{\text{sph},*}$ relation will of course refine the significance of this offset.

From a sample of 89 galaxies, Savorgnan & Graham (2015) present an updated (black hole mass)-(velocity

TABLE 2
PREDICTED BLACK HOLE MASS.

Relation	Parameter	M_{bh} prediction ($10^9 M_{\odot}$)
Sérsic $M_{\text{bh}}-M_{\text{sph},*}$	$(9 \pm 2) \times 10^{10} M_{\odot}$	$2.19^{+20.19}_{-1.98}$
Early-types $M_{\text{bh}}-M_{\text{sph},*}$	$(9 \pm 2) \times 10^{10} M_{\odot}$	$0.51^{+1.07}_{-0.37}$
Non-barred $M_{\text{bh}}-\sigma$	276 km s^{-1}	$1.35^{+2.28}_{-0.85}$

The relations are presented in Section 2.4.

dispersion: σ) diagram. It accounts for offset barred galaxies, i.e. the substructure in the $M_{\text{bh}}-\sigma$ diagram (Graham 2008; Hu 2008) and reveals that the $M_{\text{bh}}-\sigma$ relation has not saturated at high σ values due to increased dry mergers (at odds with Volonteri & Ciotti 2013, and Kormendy & Ho 2013, their section 6.7). Excluding the barred galaxies, equation 1 from Savorgnan & Graham (2015) is such that

$$\log(M_{\text{bh}}/M_{\odot}) = (8.24 \pm 0.10) + (6.34 \pm 0.80) \log[\sigma/200 \text{ km s}^{-1}], \quad (4)$$

where σ is typically the value within the inner few arcseconds. W2015 report a ‘bulge’ stellar velocity dispersion of 276 km s^{-1} within $2.''9$ (when excluding the inner $0.''44$ ‘sphere-of-influence’ based on their directly measured black hole mass of $3 \times 10^9 M_{\odot}$). This velocity dispersion gives a predicted black hole mass¹⁰ of $\log(M_{\text{bh}}) = 9.13 \pm 0.43$, or $M_{\text{bh}} = (1.35^{+2.28}_{-0.85}) \times 10^9 M_{\odot}$. Therefore, the reported black hole mass in NGC 1271 is in agreement with expectations from the $M_{\text{bh}}-\sigma$ relation, as reported by W2015.

3. DISCUSSION

3.1. $M_{\text{bh}}-M_{\text{sph}}$ relations

As revealed in Graham (2012) and Graham & Scott (2013), the $M_{\text{bh}}-M_{\text{sph}}$ distribution is bent; it is not described by a single log-linear relation. A number of simulations of galaxy evolution display a bend in the $M_{\text{bh}}-M_{\text{sph}}$ diagram, with some performing better than others at quantitatively matching the observed break and slopes (e.g. Cirasuolo et al. 2005, their Figure 5; Fontanot et al. 2006, their Figure 6; Dubois et al. 2012, their Figure 3; Khandai et al. 2012, their Figure 7; Bonoli, Mayer & Callegari 2014, their figure 7; Lu & Mo 2015; Fontanot et al. 2015). While the slope of the ‘core-Sérsic $M_{\text{bh}}-M_{\text{sph}}$ relation’ is roughly linear, the $M_{\text{bh}}-M_{\text{sph}}$ relation is steeper for the Sérsic spheroids, i.e. those without partially depleted cores (Graham & Scott 2013) — perhaps largely due to the inclusion of the bulges of spiral galaxies (Savorgnan et al. 2016).

Returning to NGC 1271, with its intermediate-scale disk, W2015 claimed that its directly measured black hole mass of $(3.0^{+1.0}_{-1.1}) \times 10^9 M_{\odot}$ is an order of magnitude larger than their expectation from the near-linear $M_{\text{bh}}-M_{\text{sph},*}$ relation that they used from Kormendy & Ho (2013). After identifying the spheroidal component of NGC 1271 and obtaining a stellar mass of $9 \pm 2 \times 10^{10} M_{\odot}$, we find that the measured black hole mass is a factor of 6.9 above the predicted black hole mass of $4.34 \times 10^8 M_{\odot}$.

¹⁰ The uncertainty on this black hole mass was derived assuming 0.3 dex of intrinsic scatter in the $\log(M_{\text{bh}})$ direction of the $M_{\text{bh}}-\sigma$ diagram and a 10% uncertainty on NGC 1271’s adopted velocity dispersion.

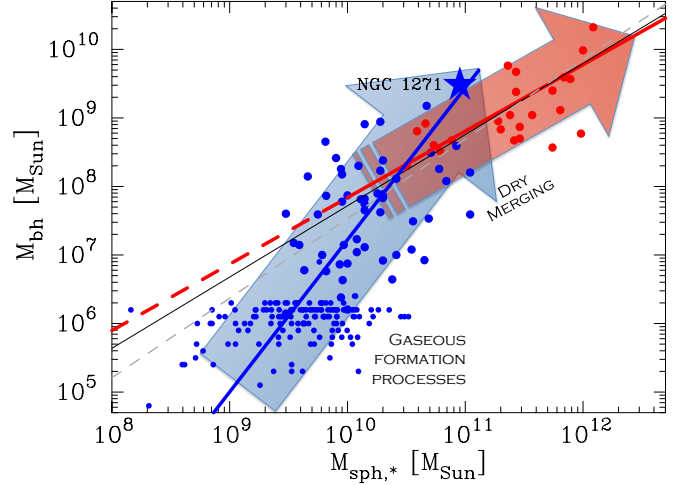


FIG. 6.— Mass tracks. The $M_{\text{bh}}-M_{\text{sph},*}$ diagram from Graham & Scott (2015), with the addition here of NGC 1271 (denoted by the star). Small blue dots denote AGN with $M_{\text{bh}} < 2 \times 10^6 M_{\odot}$, while larger blue dots denote Sérsic spheroids, and red dots represent core-Sérsic spheroids. The near-linear (log-slope = 0.97 ± 0.14) and near-quadratic (log-slope = 2.22 ± 0.58) scaling relations from Scott et al. (2013) are shown as the thick red (solid and dashed) and thick blue (solid and dashed) lines, respectively. The AGN and NGC 1271 were not included in the derivation of these scaling relations. The thin black line is the relation for early-type galaxies from Savorgnan et al. (2016), and the thin dashed grey line is the relation from Kormendy & Ho (2013).

when using the relation from Kormendy & Ho (2013, their equation 10). Savorgnan & Graham (2016a) have since provided superior image decompositions for galaxies with directly measured black hole masses, and a clear explanation of problems with many past decompositions. From their improved near-infrared magnitudes for the spheroidal components of these galaxies, Savorgnan et al. (2016) present an updated $M_{\text{bh}}-M_{\text{sph},*}$ relation for the early-type galaxies. As noted in Section 2.4, this yields a consistent black hole mass of $(5.1^{+10.7}_{-3.5}) \times 10^8 M_{\odot}$ (1-sigma uncertainties). However, the 2-sigma uncertainty ranges from $0.54 \times 10^8 M_{\odot}$ to $4.9 \times 10^9 M_{\odot}$, encompassing the reported black hole mass of $3 \times 10^9 M_{\odot}$. The reported mass is just 1.6 standard deviations away from the $M_{\text{bh}}-M_{\text{sph},*}$ relation for early-type galaxies¹¹.

It is of interest to compare the $M_{\text{bh}}/M_{\text{sph},*}$ mass ratio in NGC 1271 with other massive galaxies. Graham (2012) reported that massive spheroids with partially depleted cores (known as core-Sérsic galaxies) have an average $M_{\text{bh}}/M_{\text{sph,dyn}}$ mass ratio of 0.36% and, using a larger data sample, Graham & Scott (2013) reported an average $M_{\text{bh}}/M_{\text{sph},*}$ mass ratio of 0.49%. Kormendy & Ho (2013) subsequently reported the same ratio at $M_{\text{sph},*} = 10^{11} M_{\odot}$, and the dashed-line in Figure 6 (showing their scaling relation) largely reproduces the core-Sérsic relation from Scott et al. (2013) at high masses. The $M_{\text{bh}}/M_{\text{sph},*}$ mass ratio in NGC 1271 is $(3.0 \times 10^9)/(9.0 \times 10^{10})$, equal to 3.3%.

Rather than building a large-scale disk, perhaps ES

¹¹ The offset is even less when using the total rms scatter rather than the intrinsic scatter associated with equation 3.

galaxies with their intermediate-scale disks used their gas supplies to keep building their spheroid and black hole such that they continued to evolve along the steeper $M_{\text{bh}}-M_{\text{sph},*}$ scaling relation for Sérsic galaxies (see Figure 6). Such a scenario was described in Section 4.4 of Graham & Scott (2015). However, the rms scatter about the “core-Sérsic $M_{\text{bh}}-M_{\text{sph},*}$ relation” from Graham & Scott (2013) is 0.47 dex in the $\log(M_{\text{bh}})$ direction, in close agreement with the scatter about the $M_{\text{bh}}-M_{\text{sph},*}$ relation for early-type galaxies from Savorgnan et al. (2016), which contained less Sérsic galaxies than Graham & Scott (2013). We can therefore expect to find some galaxies with mass ratios that are $\pm 2\sigma_{\text{intrinsic}}$ (± 0.94 dex, i.e. a factor of 8.7) higher and lower than the core-Sérsic $M_{\text{bh}}-M_{\text{sph},*}$ relation. The reported black hole mass in NGC 1271 is thus consistent with the near-linear $M_{\text{bh}}-M_{\text{sph},*}$ relations. That is, it would be premature to claim NGC 1271 as an example of an over-massive black hole in a Sérsic galaxy following the steeper $M_{\text{bh}}-M_{\text{sph},*}$ relation and deviant from the near-linear relation. The high- z galaxy reported by Trakhtenbrot et al. (2015) may however evolve into such an example.

While the location of NGC 1271 in the $M_{\text{bh}}-M_{\text{sph},*}$ diagram resides almost exactly on the steep Sérsic relation from Scott et al. (2013), it should be kept in mind that this relation does contain scatter, and one data point (NGC 1271) is prone to chance alignment. If other massive early-type galaxies with intermediate-scale disks (thus keeping the galaxy compact like its spheroid) and without partially depleted cores, are found to have high $M_{\text{bh}}/M_{\text{sph},*}$ ratios like NGC 1271, then collectively they are unlikely to all be *positive* outliers from the near-linear core-Sérsic relation. Instead, they may reveal how the Sérsic $M_{\text{bh}}/M_{\text{sph},*}$ relation continues to higher masses. Preliminary reports of *elevated* $M_{\text{bh}}/M_{\text{sph},*}$ ratios (relative to expectations from the near linear $M_{\text{bh}}-M_{\text{sph},*}$ relation) in other massive Sérsic galaxies by Ferré-Mateu et al. (2015) may therefore not actually challenge the co-evolution of super-massive black holes. Rather, their host spheroid may simply be compliant with expectations from the Sérsic $M_{\text{bh}}-M_{\text{sph},*}$ relation defined by less massive Sérsic spheroids. However, as done here with NGC 1271, and in Graham et al. (2016) with NGC 1277, the spheroid masses first need to be reliably derived. This has now been done for NGC 1332, NGC 3115 and Mrk 1216 (Savorgnan & Graham 2016b)¹² and NGC 821, NGC 3377 and NGC 4697 (Savorgnan & Graham 2016a).

3.2. Compact massive spheroids - evolution or not

For decades the presence and influence of (somewhat face-on) large stellar disks in nearby early-type galaxies has frequently been over-looked. Capaccioli (1987, 1990), Carter (1987), and Capaccioli et al. (1990) campaigned for a greater awareness of these disks (see also Poulain et al. 1992 in the case of the Perseus cluster of galaxies containing NGC 1271 and NGC 1277), and the growing volume of kinematical data has since confirmed the prevalence of such disks (e.g. Nieto et al. 1988; D’Onofrio et al. 1995; Graham et al. 1998; Emsellem et al. 2011; Scott et al. 2014). Indeed, Emsellem et al. (2011, see their Figure 11), through the ATLAS^{3D} project (Cappellari et

al. 2011a), revealed that most early-type galaxies with $5 \times 10^9 < M_{\text{dyn}}/M_{\odot} < 2 \times 10^{11}$ are rotating fast within their effective half-light radii (R_e). Given their definition of M_{dyn} as twice the dynamical mass within $1R_e$, and the low fraction of dark matter within $1R_e$ for massive early-type galaxies (e.g., Cappellari et al. 2013), the above observation also holds true for the stellar mass range $10^{10} < M_*/M_{\odot} < 2 \times 10^{11}$. While kinematical maps also now readily betray the presence of *intermediate-scale* disks (see also Figure 9 from Krajnović et al. 2013), care is still required when modeling and interpreting the host galaxy’s distribution of stellar light and assigning it to physical components such as disks, spheroids, etc. (e.g. Savorgnan & Graham 2016a; Sil’chenko 2016).

In passing we briefly discuss the nice kinematic maps for NGC 1271 presented in W2015. Their Figure 6 includes a velocity map over the inner $\sim 12 \times 24''$ in which the contribution from the disk can be seen to peak along the major-axis at $\sim 8''$ and then decline with radius, mimicking the behavior of the ellipticity profile seen in Figure 3. In addition, their absorption line map of the h_3 asymmetric deviations of the line of-sight velocity distribution from a Gaussian reveals a disk whose dominance reaches $r_{\text{major}} \approx 15''$, mimicking the behavior of the B_4 profile seen in Figure 3. The dynamical model shown in their Figure 6 can also be seen to rotate with a greater velocity at large radii than is supported by the data. Figure 9 in W2015 (based around their 11-component luminous mass model) shows the gradual returning importance of the bulge beyond $\sim 10-16''$, as is also seen in our decomposition (Figure 3). We expect that more extended, major-axis kinematic data (beyond $24''$) will solidify the embedded/truncated nature of the disk in NGC 1271 and support our two-component model for the bulk of this galaxy’s stellar flux. Within the isophote having a major-axis equal to $24''$, our model has some 77% of the flux in the spheroidal component and 23% in the flattened disk. This is at odds with W2015 who reported that “the bulge component accounts for 12% of the mass, whereas the rotating components total 75% of the mass within the radial extent [$r_{\text{major}} \approx 24''$] of the kinematic measurements”.

Graham (2013) suggested that many of the compact spheroids at $z \sim 2 \pm 0.5$ (e.g. Weinzierl et al. 2011; Damjanov et al. 2014; van Dokkum et al. 2015, and references therein) may not have grown in size — as commonly thought — because compact spheroids are still around us today (Figure 5), with NGC 1271 another such example. Indeed, the mass, half-light radius, velocity dispersion and rotation of NGC 1271 match reasonably well with the recently quenched galaxy RG1M0150 observed at $z = 2.636$ by Newman et al. (2015). It is just that most local, compact massive spheroids are now connected with stellar disks (see the simulations by, and Figure 2 in, Wellons et al. 2016 which supports this growth path). Rather than transforming these compact spheroids through minor dry mergers, Graham (2013) speculated that disk building might have been in operation.

This represents a fundamentally different formation path and evolutionary history: the former is thought to build elliptical galaxies, while the latter builds both S0

¹² At the time of submission (9 July, 2015), Savorgnan & Graham (2016b) was work in prep.

galaxies¹³ and ES galaxies.

This is a simple and elegant solution which has since been supported by the results in de la Rosa et al. (2016) and Margalef-Bentabol et al. (2016). Moreover, it matches with evidence for nascent disks at high- z (e.g. Longhetti et al. 2007; van der Wel et al. 2011), and with new 870 μm continuum emission observations of hot dusty galaxies at $z \sim 2$ which reveal the presence of compact massive bulges in pre-existing large-scale disks (Tadaki et al. 2016; Barro et al. 2016). If these disks subsequently grow in stellar mass, and thereby effectively increase their *galaxy's* half light radius, they will then be matched with observations of local lenticular galaxies. If, instead, (3D envelope)-building minor-mergers was the common mechanism for growing the size of (many of) the compact massive galaxies seen at $z \sim 2$, then most of the massive early-type galaxies in the local universe (not to be confused with the most massive galaxies in the local universe) should be pressure-supported elliptical galaxies. They are not. Furthermore, dry minor mergers are at odds with the $z \approx 1.2$ galaxy size/age results of Williams et al. (2016), and minor mergers can destroy stellar disks according to Khochfar et al. (2011). Moreover, too much merging will introduce scatter not seen in the galaxy scaling relations (Nipoti et al. 2009). Although, it is noted that satellite galaxies display a tendency to reside in a plane (Kroupa et al. 2005; Welker et al. 2015), possibly favoring disk formation.

While large, massive elliptical galaxies are known to exist at $z \sim 2\text{--}3$ (e.g. Mancini et al. 2010; Newman et al. 2010; Saracco et al. 2010), and major mergers will build more by today (e.g. NGC 5557, Duc et al. 2011) — with the super-massive black holes from the progenitor galaxies scouring out a partially depleted core when it is a dry merger event (e.g. Gualandris & Merritt 2012, and references therein) — it is now recognized that most nearby early-type galaxies with $10^{10} < M_*/M_\odot < 2 \times 10^{11}$ are comprised of a compact spheroidal component plus a stellar disk (e.g. Emsellem et al. 2011; Krajnović et al. 2013). This suggests that disk growth, rather than messy mergers, may be how many of the compact massive galaxies at $z \sim 2\text{--}3$ have grown in size. In this scheme, rather than staying on the ‘red-sequence’ since $z \sim 2\text{--}3$, gas disks are accreted around the compact, massive high- z galaxies (e.g. Birnboim & Dekel 2003; Kereš et al. 2005, 2009; Dekel et al. 2009), stars then form in these disks and the galaxies move to the ‘blue cloud’ and likely partake in high star formation rates before the disks then rapidly reduce much of their star formation by $z \sim 1 \pm 0.2$ (e.g. Madau et al. 1998; Dickinson et al. 2003; Pérez-González et al. 2005) to produce the more massive ES and S0 galaxies around us today. Due to ‘downsizing’ (Noeske et al. 2007; Pérez-González et al. 2008a,b), the tail-end of disk growth in less massive early-type galaxies is still occurring in some early-type galaxies today (e.g. Lemnias et al. 2011; Moffett et al. 2012; Alatalo et al. 2013; Bayet et al. 2013; Geréb et al. 2016; GDS15, see their section 4.1 and references therein). This scenario of disc growth is not just a solution to the fate of the compact massive $z \sim 2\text{--}3$ galaxies, but simultaneously answers an-

other question which oddly has not been asked: Where, in the $z \sim 2\text{--}3$ universe, are the precursors of the old, compact massive spheroids seen in local elliptical¹⁴ (ES), lenticular (S0), and massive spiral (Sp) galaxies?

3.3. *Placing galaxies with intermediate scale disks in a familiar classification diagram*

The existence of intermediate-scale disks led to suggestions of a likely continuum of disk sizes in early-type galaxies (see Simien & de Vaucouleurs 1986; Capaccioli et al. 1988; Bender 1989; Simien & Michard 1990; Scorza 1993; Scorza & van den Bosch 1998). The presence of these intermediate-scale disks blurs the distinction between elliptical (E) and lenticular (S0) galaxies, or slow-rotators (SR) versus fast-rotators (FR), see Cappellari et al. (2011b, their Figures 1 and 2). That is, there is a need for more than two bins (i.e. nuclear vs. large-scale disk, E vs. S0, SR vs. FR), and a need for a continuum in (Hubble-Jeans)¹⁵-like classification schemes.

It has been argued that the classification scheme for “elliptical” galaxies should not be their apparent ellipticity, set by their observed axis ratio (originally E0–E7, see Hubble 1936 and Sandage 1961; then E0–E4 when it was realised that the E5–E7 galaxies are S0s, see Liller 1966 and also Gorbachev 1970), because this depends on our viewing angle rather than being intrinsic to the galaxy. Obviously when dealing with intermediate-scale disks, the disk shape of the isophotes is a function of both the disk’s inclination *and* the isophotal radius, making this single isophotal shape parameter problematic and particularly inappropriate for the ES class. Section 4 of Kormendy & Bender (1996) points out additional complications in regard to this.

Early-type galaxies may be better quantified by their spheroid-to-total flux ratio, with a continuum from pure elliptical galaxies to disk-dominated lenticular galaxies (e.g. Capaccioli et al. 1988, and references therein). This spheroid-to-total flux (or better mass) ratio is widely recognized as an important quantity, and its broad range observed in the lenticular galaxies led Cappellari et al. (2011b) to present the “Hubble comb”. This built on van den Bergh’s (1976) diagram in which both late-type galaxies (i.e. spiral galaxies) and early-type galaxies form separate prongs of an expanded Hubble-Jeans tuning fork, with an additional prong for disk galaxies hosting anaemic spiral patterns. Cappellari et al. (2011b, see also Kormendy & Bender 2012) presented a scheme in which the morphological type (a, b, c, etc.) changed if the spheroid-to-total ratio changed. *However*, the primary criteria used to assign the spiral galaxies’ morphological type (a, b, c, etc.) over the last half century (Sandage 1961) has been the nature of the spiral arms — the extent to which they are unwound, pitch angle, and the degree of resolution — rather than the spheroid-to-total ratio. Indeed, in the Hubble Atlas of Galaxies, Sandage (1961) notes that Sa type galaxies exist with both small and large bulges, see

¹⁴ While working on this project we informally used this term to denote the ‘disk elliptical’ ES galaxies intermittent between elliptical and lenticular galaxies.

¹⁵ As noted by van den Bergh (1997) and Sandage (2005), it was Sir James Jeans (1928) who introduced the (tuning fork)-shaped diagram that encapsulated Hubble’s (1926) elliptical-spiral sequence — itself motivated by the earlier work of Jeans (1919).

¹³ See Bois et al. (2011) and Querejeta et al. (2015) for an alternative pathway to build some lenticular galaxies from spiral galaxies.

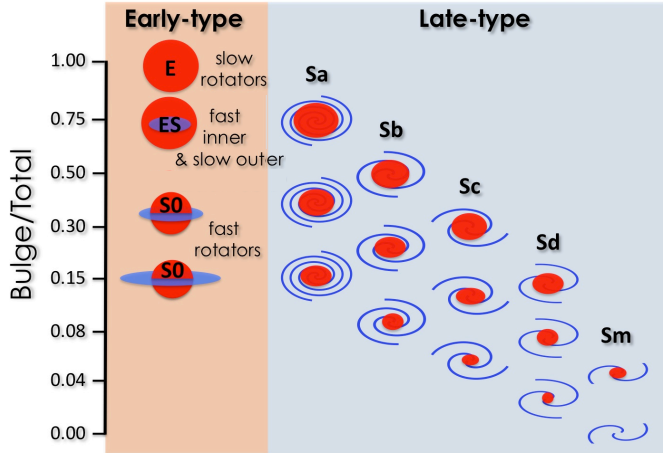


FIG. 7.— Grid showing the location of *elliptical* (ES) galaxies, intermediate between elliptical (E) and lenticular (S0) galaxies, relative to the spiral galaxies. The horizontal axis shows the morphological type, primarily dictated by the nature of the spiral arms.

also the “Morphological Catalogue of Galaxies” (MCG) from Vorontsov-Vel’Yaminov & Arkhipova (1962) and Vorontsov-Vel’Yaminov & Noskova (1973).

The early-type galaxies, as with the Sa type galaxies, and the Sb type galaxies, and the Scd type galaxies, etc. all have a range of bulge-to-total mass ratios. Despite recent claims to the contrary, the fast rotating early-type galaxies do not span the same full range of bulge fractions as spiral galaxies. Indeed, there are bulgeless spiral galaxies but there are not bulgeless early-type galaxies. Morphological types have been meticulously assigned to thousands of spiral galaxies, but because this was not primarily based on the bulge-to-total ratio, it obviously can not now be used to represent the bulge-to-total ratio in a revised Hubble-Jeans tuning fork diagram. To do so would be a mistake. One could however ignore this morphological type information and instead use bulge-to-total ratio as one axis, with additional markers indicating if the galaxy has a strong or weak or no bar, or has a strong or anaemic or no spiral pattern.

The grid seen in Figure 7 and discussed in Graham (2014) is a slight variant of that used by Freeman (1970, his Figure 9), Boroson (1981), Kent (1985), Kodaira et al. (1986), Simien & de Vaucouleurs (1986) and others, and allows for the varying spheroid-to-total ratio among each galaxy type (a, b, c, etc.). This older classification scheme provides a complementary view of the galaxies; it captures both the morphological type information along one axis and the spheroid-to-total ratio along the other. Importantly, Figure 7 shows where the early-type galaxies with intermediate-scale disks (ES) reside relative to the other Hubble galaxy types in this familiar diagram which has tended not to include the E and ES galaxies to date. Rather than using the extended classification scheme for early-type galaxies (E - E⁺ - L⁻

- L^o - L⁺ - S0, corresponding to the numerical T-type ranging from -5 to 0, e.g., de Vaucouleurs et al. 1964, Heidmann et al. 1972), they are grouped together in the single left-hand column of Figure 7 instead of extended horizontally to the left (e.g. Andreon & Davoust 1997, their section 5). While, collectively, spiral galaxies typically display a range of spheroid-to-total flux ratios from 0 to 3/4 (e.g. Graham & Worley 2008, and references therein), lenticular galaxies commonly display a range from 0.1 to 3/4 (Laurikainen et al. 2010), and the ES class have larger ratios.

4. CONCLUSIONS

The black hole mass predicted by W2015 was lower than they expected because the embedded, intermediate-scale disk in NGC 1271 (evident in Figure 1 and the lower panels of Figure 3) led to some confusion as to what is the ‘spheroidal’ component of this galaxy. Some early-type galaxies have not managed to grow their disks into the more easily identified large-scale disks seen in many lenticular galaxies. When this happens, the spheroidal component of these ES galaxies remains larger than their disk component, and thus the spheroid not only appears as a central “bulge” but it also dominates the light at large radii. Having modeled the distribution of light in NGC 1271 with an embedded intermediate-scale disk (Figure 2 and the upper panels of Figure 3, see also Figure 4), we report that the full spheroid stellar mass in NGC 1271 is $9.0 \times 10^{10} M_{\odot}$, greater than that adopted by W2015 ($5.4 \times 10^{10} M_{\odot}$). We additionally report that this spheroid is consistent in the size-mass diagram with other (relic) spheroids found in massive early-type disk galaxies (Figure 5).

Much of the thrust of the W2015 paper arose from the suspected order of magnitude offset of NGC 1271 from a near-linear $M_{\text{bh}}-M_{\text{sph},*}$ relation in the $M_{\text{bh}}-M_{\text{sph},*}$ diagram. However we find that NGC 1271 is not an unusual outlier in this diagram (Figure 6). The black hole mass in NGC 1271 is only 1.6-sigma above the near-linear $M_{\text{bh}}-M_{\text{sph},*}$ relation for early-type galaxies (Savorgnan et al. 2016). Therefore, the idea that NGC 1271 may represent a galaxy whose black hole and host spheroid co-evolved in accordance with the steep near-quadratic $M_{\text{bh}}-M_{\text{sph},*}$ relation to particularly high masses — as discussed in Graham & Scott (2015) — and resulting in a *significant* departure from other massive spheroids, is not supported by the data (see Figure 6).

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